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THE EXCHANGE OF WATER BETWEEN THE RED SEA AND THE GULF OF ADEN OVER THE "SILL"

BY

E. F. THOMPSON, M.Sc.(N.Z.), Ph.D.(Cantab.)

WITH TEN TEXT-FIGURES

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As was pointed out in a previous paper (Thompson, 1939), the Red Sea "proper" is separated from the Gulf of Aden by a shallow sill near the Hanish Islands. This sill reaches its maximum height at about latitude 13° 41′ N., where the depth of water is only 100 metres; the bottom then falls away rapidly to the considerable depths of the Gulf of Aden. Most previous workers have used stations further south in the neighbourhood of Perim; but the depths found by the "Mabahiss" (Sewell, 1936) show quite clearly that the real separation between the Red Sea and the Gulf of Aden occurs, not here, where the channel is narrowest, but in latitude 13° 41′ N., where it is shallowest.

A number of investigations of this area have already been carried out. The earliest of these was that of the "Stork", and in 1897 the "Pola" (Luksch, 1901) carried out extensive work here. On this data are based the conclusions of Krummel (1911). These deductions have been severely criticized by Vercelli (1927), and their validity, indeed, seems to be extremely doubtful. More recently very extensive investigations of the currents and physico-chemical properties of the water in this region have come from the "Magnaghi" (Vercelli, 1927 and 1930; Picotti, 1930). All these sets of data agree in showing a surface current flowing into the Red Sea from the Gulf of Aden, and a deep flow of more saline water in the opposite direction. The results of the "Ormonde" have been published by Matthews (1927); and he has given a comparison of these results with those of the "Magnaghi" (Matthews, 1928). These two papers are chiefly concerned with the water on the Gulf of Aden side of the "Sill".

All this work has been summarized by Schott (1929). This author discusses the similarity between the interchange at Gibraltar and here. He points out that the position

of the " Sill " is outside the enclosed sea at Gibraltar and inside here. At Gibraltar there is no complete change of the wind system in the two seasons, while here the wind system goes through a complete seasonal reversal, blowing from the NNW. during the summer and from the SSE. during the winter. He has drawn a section from the Red Sea to the latitude of Aden in which he shows the $38{\cdot}0^{\circ}/_{\circ\circ}$ isohaline continuous all the way from the Red Sea to the top of the Gulf of Aden. He points out that, though the upper end of the Gulf is, probably, in the deepest layers normally filled with water of a salinity $>37^{\circ}/_{\circ\circ}$, there is " good reason " for supposing that water of a salinity $>38^{\circ}/_{\circ\circ}$ must be only a temporary phenomenon, perhaps due to an intermittent flow from the Red Sea. He also states that the reversal of the winds is such that in the summer months, when the need for replacement of water lost by evaporation in the Red Sea is greatest, the wind system would tend to oppose the compensating inward flow. Of this anomaly he offers no explanation. In view of our previous ignorance of the nature of the exchange here, Schott's work (1929) was a real contribution to our knowledge of these conditions. Unfortunately the paucity of available data forced him to consider stations from widely different times and seasons in the same section. As will be seen from the present paper, this is inadmissible here. Most of the points left by Schott as " undetermined " can be explained when the distinct nature of the exchange in the two seasons is realized.

The most valuable previous work is that of Vercelli (1927 and 1930) on the tide-induced internal waves at the boundary between the inflowing surface and outflowing deep water (" neutral level " of Vercelli). He has shown that they are such that, at the " neutral level ", the salinity increases with the flood tide, flowing into the Red Sea, and decreases with the ebb tide. The temperature shows a correlated variation. An explanation of these thermohaline oscillations, dependent on the rhythm of the tide and tide currents, is probably to be found in the explanation already suggested by Schott (1928) for the very similar oscillations in the Straits of Gibraltar. The average winds in these straits have already been described (Thompson 1939) : from October to April they are southerly, and from May to September, northerly. In the deep water of the Red Sea a considerable lag in the change-over of the current system was to be expected, so that the maximum effect of each season was to be found in the early stages of the succeeding one. In these straits the water is comparatively shallow, so that the lag will be less, and an ideal time for examining the complete result of each season would be just at the end of that season, *i. e.* in September and April.

CONSIDERATION OF DATA.

The treatment of the data, preparatory to its use in the construction of the following sections, is similar to that previously described (Thompson, 1939).

The material considered in the present discussion consists of five stations carried out by the John Murray Expedition in September (Nos. 6, 7, 8, 9, 13), and repeated in May (Nos. 208, 206, 204, 203, 201). It will be seen that the former series of observations are almost at the ideal time, while the latter, being about a month late, will tend to be confused by the effect of the succeeding season. In each case, so as not to crowd the sections, the first and last stations in each series have been omitted ; but they have been used in the extrapolation from the middle three stations. The positions of the ten stations are shown in Text-fig. 1. In the sections the vertical scale is 185 times as large as the horizontal

scale, the distance from Station 7 to Station 9 (or Station 206 to 203) being about 25 sea miles.

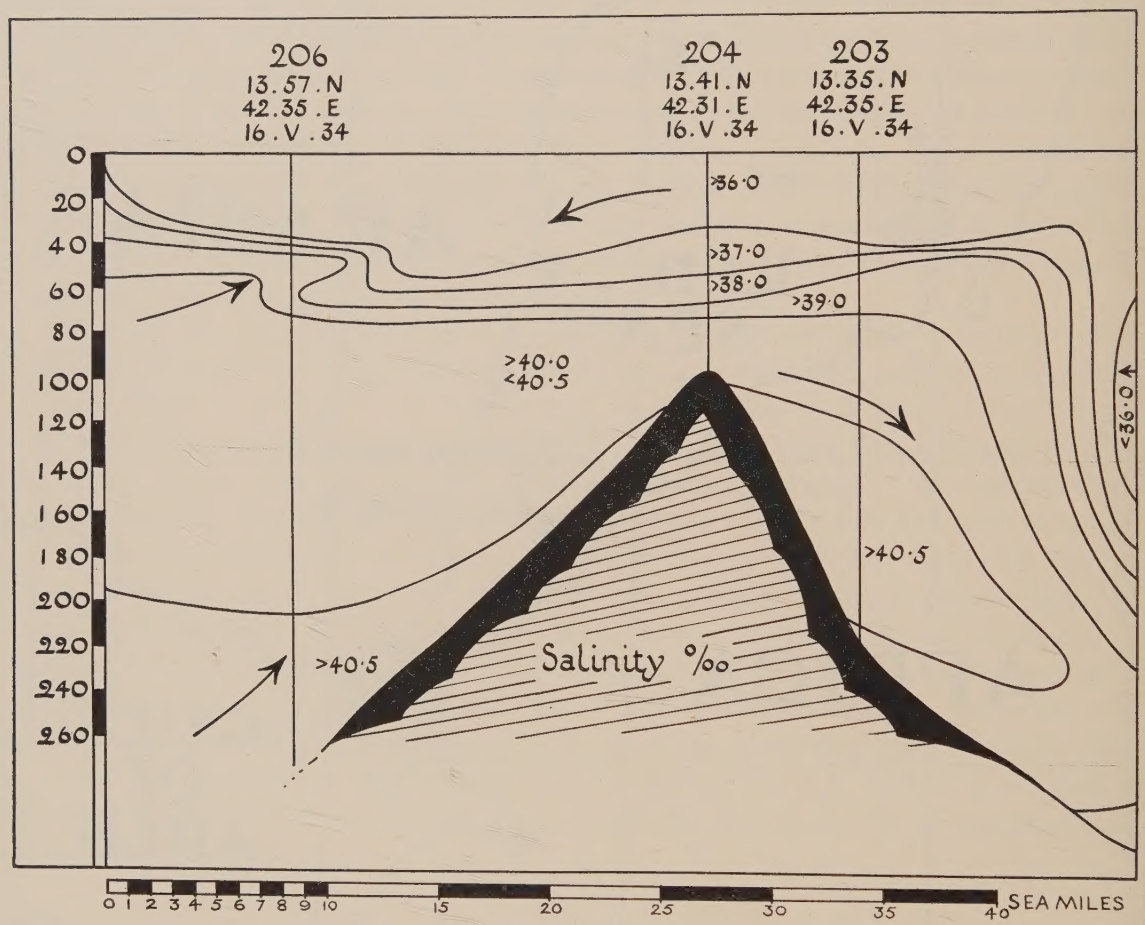
TEXT-FIG. 1.

Arrows are used to indicate the direction of transport during the particular season; and while the actual trajectories during the season will largely coincide with these, at the ends of these seasons the movements will be at a minimum.

THE EXCHANGE AT THE END OF THE WINTER SEASON. (WIND SE.)

The Distribution of Salinity in May.

The course of the 37°/$_{oo}$ isohaline gives a clear indication of the wind-driven surface current to be expected in this season. It comes in from the surface water of the Gulf of Aden. Between the surface layers and the deeper water is a very sudden discontinuity showing relatively enormous stability (Text-fig. 10). It occurs between 40 and 50 metres at Station 203, 30–40 metres at Station 204, and 60–80 metres at Station 206. It seems



Text-fig. 2.

probable that this discontinuity marks the limiting depth to which active wind transport occurs, *i. e.* the depth of the wind-driven surface current.

Beyond Station 206 towards the Red Sea the isohalines gradually turn up on coming into the more highly saline water of the Red Sea. At Station 206 there is an interesting bend in all the isohalines from 37°/$_{oo}$ to 40°/$_{oo}$. The explanation of these bends may be found in two different factors. It may be the beginning of the reverse stream characteristic of the summer season which has just begun; but more probably it is the point of meeting of the highly saline upward-moving deep Red Sea water with the inflowing lower salinity Gulf of Aden surface water. The distribution of temperature and oxygen supports the latter view.

The course of the 40·5°/$_{oo}$ isohaline shows clearly the upward movement of highly saline deep Red Sea water on the north of the barrier, and its subsequent downpouring into the Gulf of Aden.

A very interesting feature is seen at the extreme right of the figure between 60 and 140 metres. Here the isohalines run almost vertically and are very close together, falling rapidly from 39 to 36. This aggregation is no doubt due to the highly saline deep Red Sea current coming into contact with a mass of low salinity Gulf of Aden water. Schott (1929) has assumed that this water of very low salinity is part of the surface current flowing from the Gulf of Aden into the Red Sea at this season. But the general course of the isohalines suggest that this is not so, and that the surface current with its higher salinity (>36 as against <36) is derived almost entirely from the surface water of the Gulf of Aden, and that during this season this deeper water mass is almost entirely blocked from entrance to the Red Sea by the outflowing Red Sea current. No doubt as this low salinity mass comes into contact with the deep Red Sea water, some of it will be projected upwards and will then mix, at least to a limited extent, with the upper wind-driven current. But it seems clear that the great mass of the surface current, with very different salinity, temperature and oxygen, is of quite different origin.

At Station 204 there is a very definite bend in the 37°/$_{oo}$ isohaline. Probably this has its explanation in the tide-induced oscillations which Vercelli (1927) has already described.

The existence of a mass of water of salinity >40·5°/$_{oo}$ on the outside of the barrier, with a break at the shallowest level (Station 204), suggests that here we have an indication of the phenomenon described by Vercelli (1927). He pointed out that the isohalines rose while the tide was flowing into the Red Sea, and possibly the break in the 40·5 isohaline is due to the state of the tide ; in this case the outflow of water of a salinity 40·5°/$_{oo}$ would be a transitory phase, occurring at the flood tide. Such an explanation appears to be probable in view of the fact that the observations at Station 204 were taken between 9.20 and 10.40 a.m. on May 16th, 1934, on which day high tides, height 5·9 ft., occurred at Perim at 11.12 a.m., so that the tide was flooding. An alternative explanation is that there may be a deeper channel between the Red Sea and the Gulf of Aden. But our fairly complete " echo " soundings, which would hardly miss such a channel, as well as those already charted, show no indication of it.

With reference to the question left over by Schott (1929) as to whether the outflow of water of a salinity of 38°/$_{oo}$ was a continuous or temporary phenomenon, these observations seem to indicate that the former is the case. Especially is this so in view of the fact that the 38°/$_{oo}$ isohaline runs almost level from Stations 206 to 203. These stations were worked at hours 0710, 1920, 1301, *i.e.* over a 6-hour period, and so it is impossible that they can all be at the same stage in the oscillations which Vercelli has shown to have a period of approximately 12 hours. Thus it would seem that the continuity of the 38°/$_{oo}$ isohaline is permanent *at this season* over all stages of the tide.

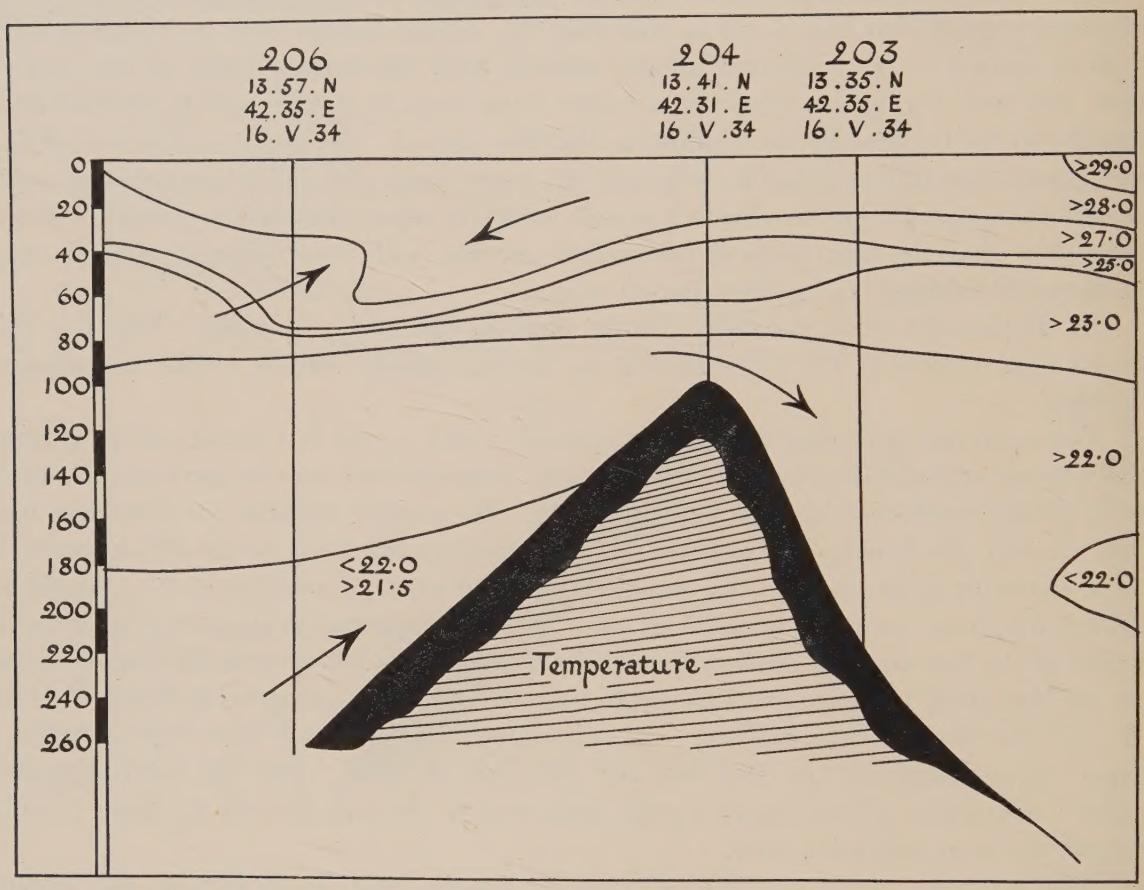
The Distribution of Temperature in May.

In Text-fig. 4 the course of the 28° isotherm marks off the wind-driven, warm current flowing from the Gulf of Aden into the Red Sea. Its very high temperature indicates that the water is almost entirely of surface origin. At Station 206 we have a sudden

bending of the 28°, 27° and 25° C. isotherms, indicating that here the inflowing, warm surface current comes into contact with the " upwelling " deep Red Sea water. The nature of the change makes the other suggested explanation seem unlikely ; but it is quite possible there is a large eddy here.

At Station 204 we see a bending of the 25° C. isotherm quite comparable with that seen at this point in the salinity figure, and with the same significance.

On the extreme right of the figure is a zone of low temperature at about 175 metres, indicating the presence of the low salinity water seen in the salinity figure. Its very low



Text-fig. 3.

temperature makes it impossible that this mass of deep water can make any considerable contribution to the high temperature surface current, as suggested by Schott (1929).

The Distribution of Oxygen in May.

In Text-fig. 4 the inflowing surface current is not very strongly indicated, but at Station 206 the bend in the 4 c.c./l and 3 c.c./l lines is further evidence that deep Red Sea water is here coming into contact with the inflowing surface stream. The course of the 1 c.c./l line within the Red Sea is a further indication of the deep upward movement in this region. On the extreme right of the figure a very low oxygen value is found at about 170 metres occupying the same position as the low salinity and low temperature water mass seen in the previous figures. The very low value of this oxygen is additional evidence

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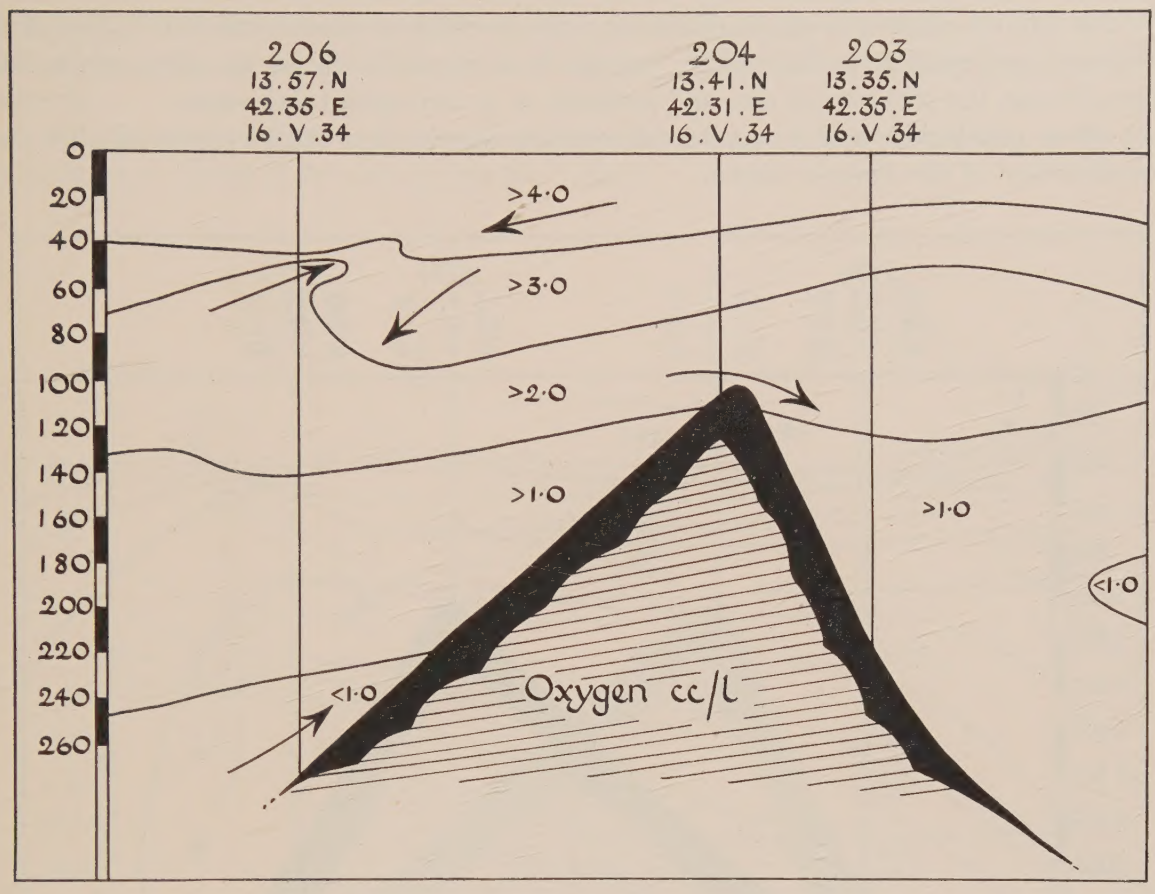
that there can be little mixing between this water and the highly oxygenated surface water flowing into the Red Sea.



Text-fig. 4.

The Distribution of Density in May.

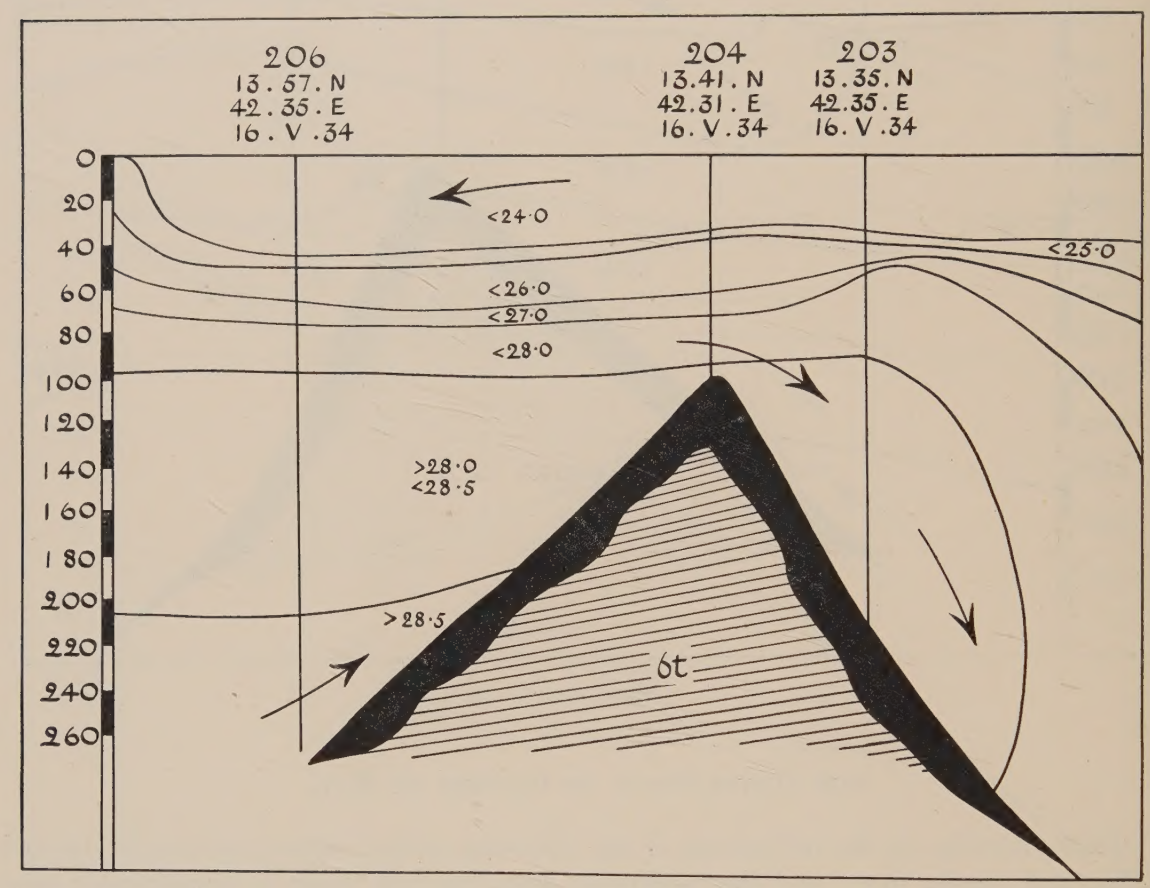
Here (Text-fig. 5) the indications of the inflowing surface stream are clearly marked by the 25·0 density line ; and the outflowing deep Red Sea water is unmistakably seen in the down-curving of the 28·0 line beyond Station 203. The sudden change of density between the surface current and this deeper upward movement shows clearly the abrupt discontinuity between these two currents, which is so sharply defined that there can be little mixing between them. It is at this level that Vercelli (1927) found the maximum development of his tidal oscillations, and the great size of these is no doubt due to the great stability existing between these two water masses.

In these four figures the conditions prevailing at the end of the winter season are quite clearly shown. All the extensive investigations in this region have been carried out during this season ; and this more detailed study enables us to amplify and correct the previous conclusions. The course of the inflowing surface current and the existence of an outward bottom movement, already recognized by previous workers, is unmistakable, but, whereas Schott (1929) derived this surface current largely from the water in the Gulf of Aden down to 200 metres, it is here shown that this deeper water can contribute but

slightly to the water in the surface current. The surface current is almost entirely derived from Gulf of Aden surface water; and the water below 100 metres is part of a totally different system, the origin of which will be considered in the next section.

No definite conclusion can be drawn from this work as to whether the 38·0°/$_{oo}$ isohaline is always continuous over the "Sill"; but this is obviously so during the phase of the tide when Station 204 was carried out, and probably is so throughout *this season*.

Other conclusions which may be drawn from these figures will be discussed after the consideration of the summer season.



Text-fig. 5.

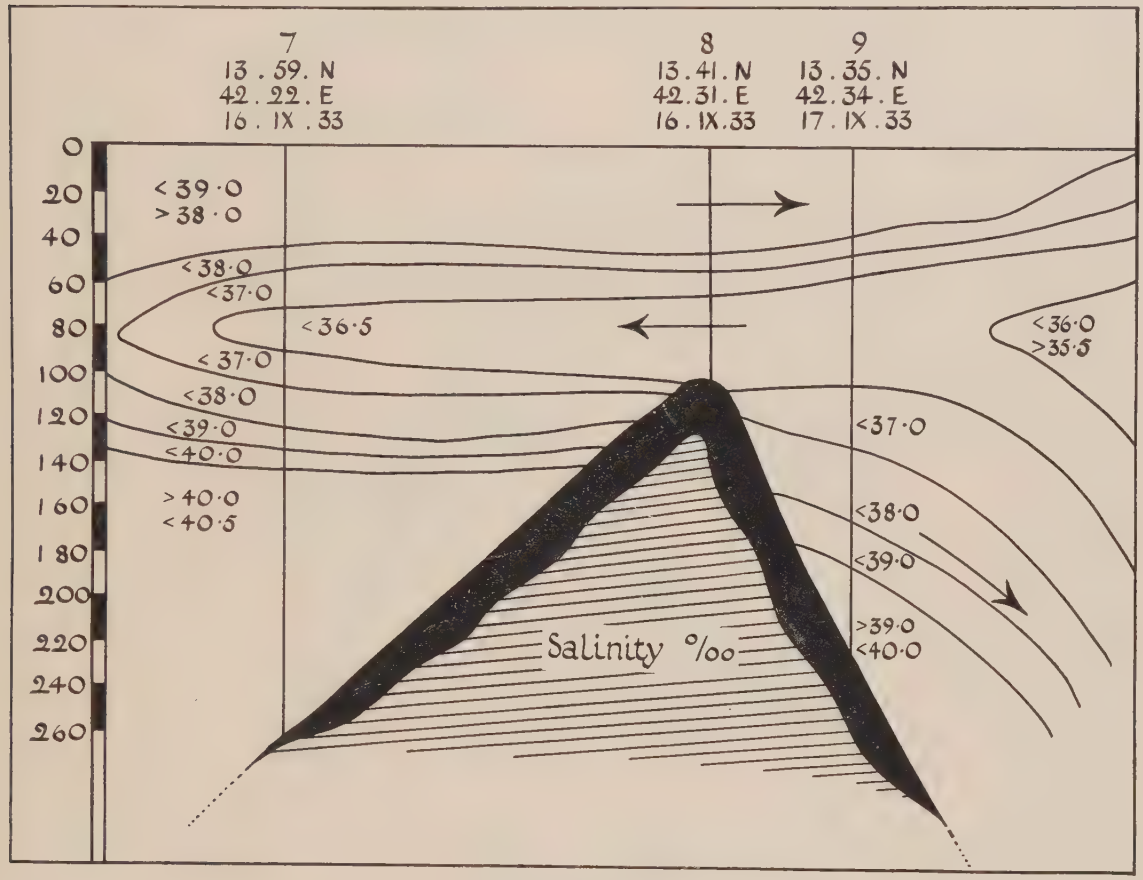
THE EXCHANGE AT THE END OF THE SUMMER SEASON. (WIND NNW.)

The Distribution of Salinity in September.

In Text-fig. 6 the course of the upper 38·0°/$_{oo}$ isohaline clearly indicates the highly saline outflowing current from the Red Sea. This is to be expected in view of the NNW. wind blowing during this season. Below this line the salinity falls rapidly, reaching a minimum of less than 36·5°/$_{oo}$ at about 80 metres. Below this point the salinity again rises rapidly. The course of the isohalines from the lower 37·0 line down to 40·5, their upbending on the left of the figure and their down-curving from Station 9 out towards the Gulf of Aden indicates that here again we have an outflowing of Red Sea water from the deeper layers. At the "Sill" itself, however, these lines are interrupted, and it must

be assumed that they are continuous only during the flood tide and are at this season broken during the ebb. Such a conclusion would be in agreement with the vertical oscillations of the isohalines at the " neutral level " (Vercelli, 1927); in this connection it is significant that the size of the vertical oscillation necessary to make the 39·5°/$_{oo}$ isohaline continuous at the sill is about 40 metres, the oscillation actually found here by Vercelli.

On the extreme right of the figure at about 80 metres we find the nucleus of the low salinity water found at 80 metres over the " Sill ".



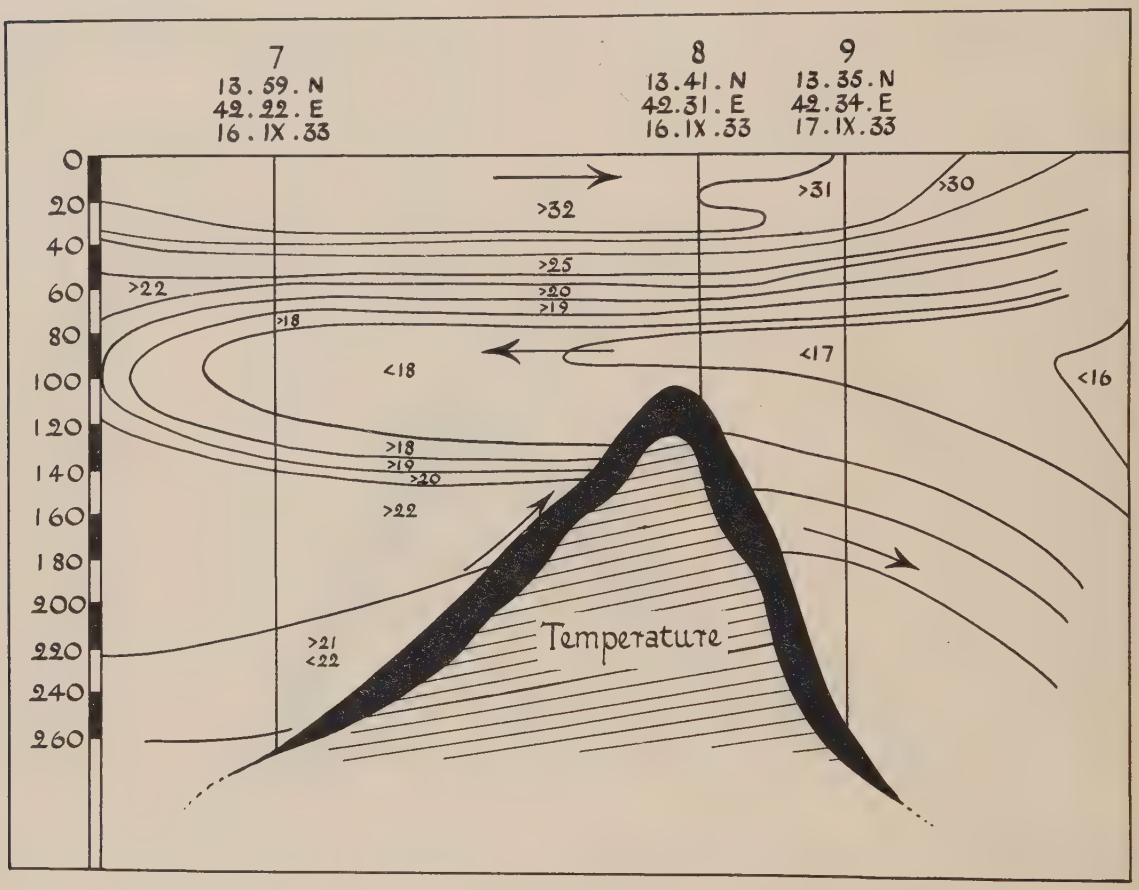
Text-fig. 6.

From this figure it can be seen that during this season there are three currents flowing over the " Sill ", a surface wind-driven outflowing current of high salinity, a middle low salinity current with its nucleus at about 80 metres flowing into the Red Sea, and a deep highly saline body of water moving from the Red Sea to the Gulf of Aden presumably during the flood tide.

The Distribution of Temperature in September.

As in the salinity section (Text-fig. 6), here (Text-fig. 7) we can recognize quite clearly the existence of three bodies of water. At the surface there is a very warm current flowing from the Red Sea to the Gulf of Aden, while below this there is a much colder stream in

the reverse direction, with its nucleus at about 80 metres. Below this point the temperature rises rapidly to about 22° C., and we here encounter the outpouring deep water from the Red Sea. At Stations 7, 8 and 9 the very rapid temperature discontinuity between these three bodies of water is clearly marked. The lower isotherms are interrupted at the "Sill", and the explanation of their reappearance on the Gulf of Aden side of the "Sill" is the same as that offered for the similar phenomenon seen in the isohalines, namely a tidal oscillation.

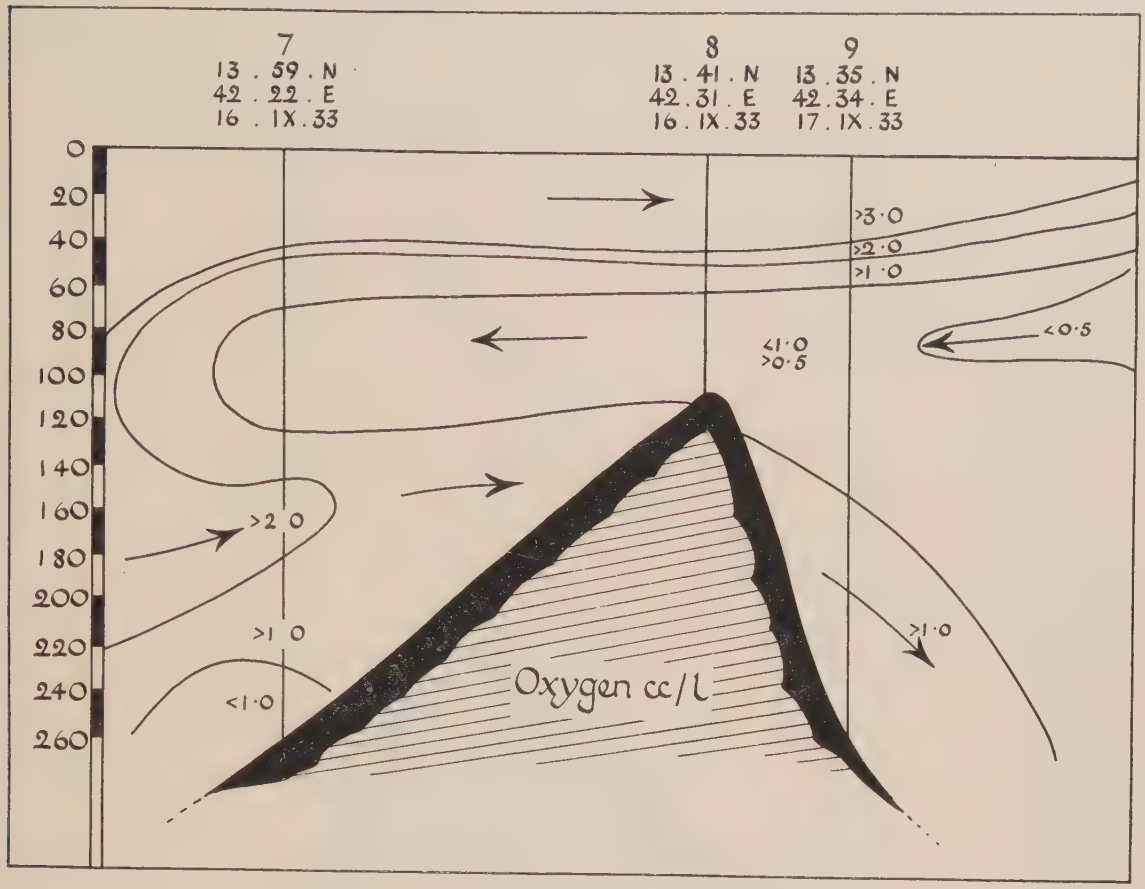


Text-fig. 7.

The Distribution of Oxygen in September.

In Text-fig. 8 the three bodies of water already mentioned can again be seen. At the surface is the highly oxygenated outflowing Red Sea water, and below this is water with a very low oxygen concentration flowing from the Gulf of Aden to the Red Sea. Below 100 metres at Station 7 the rapid secondary rise of the oxygen shows that we have here entered the lowest body of water, the deep Red Sea stream. There is some overlap between the different currents, but the 1 c.c./l line approximately delimits the three bodies of water. The subsequent fall of oxygen at 240 metres at Station 7 might seem to suggest that here there is some admixture with the deoxygenated water from the Gulf of Aden, but as this is not indicated in the salinity or temperature figures, a more probable

explanation is that here we have a more or less stagnant portion of water caught between the seasonal oscillations of the Red Sea and the " Sill ".



Text-fig. 8.

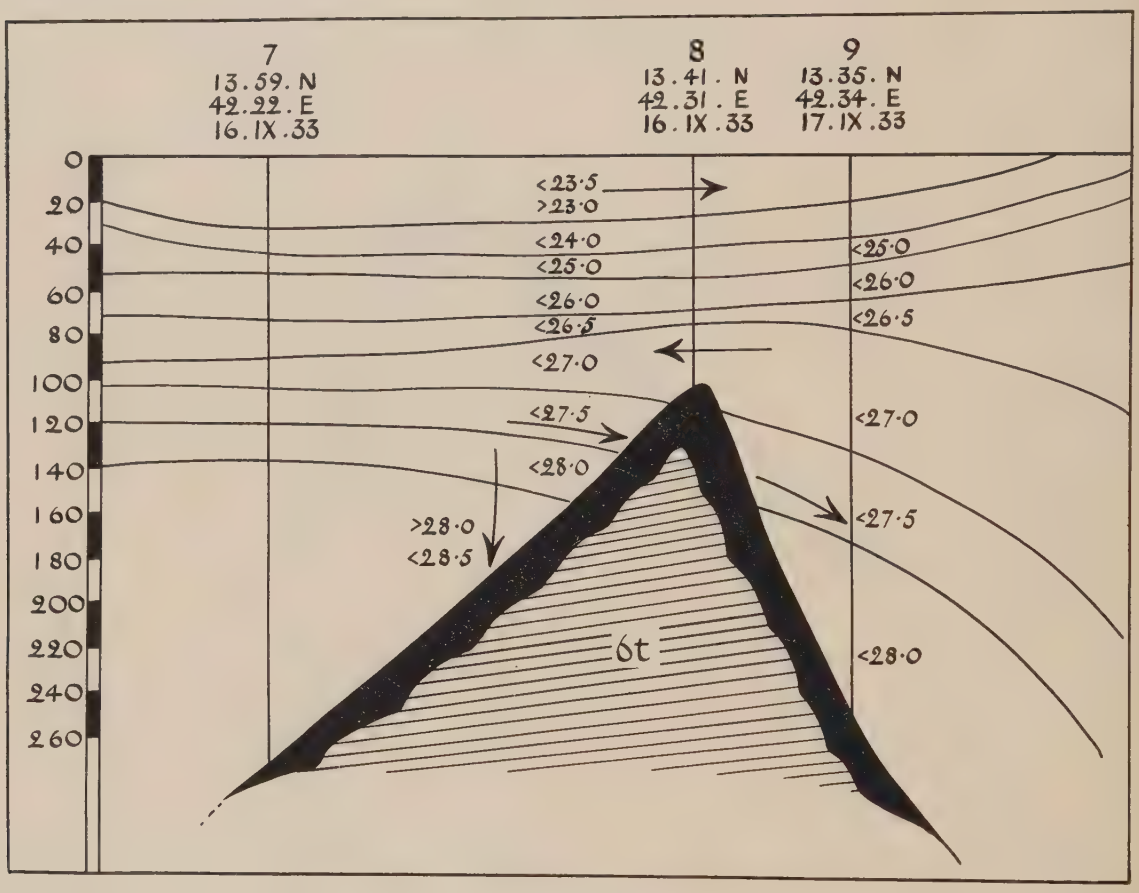
The Distribution of Density in September.

The phenomena already discussed in the previous three figures are not quite so clearly shown here; but the general trend of the three main bodies of water is quite definitely indicated. At the surface is a very light body of water due to the outflowing warm saline Red Sea stream roughly limited by the course of the 24·0 isostere; while at the bottom the course of the 27·0 and 27·5 density lines indicates the outpouring of deep Red Sea water. The inflowing subsurface Gulf of Aden stream is best indicated by the separation of the 26 and 26·5 density lines on the extreme right of the figure at a depth of about 80 metres and their subsequent convergence at Station 8. That these lines do not show the further passage of this current into the Red Sea is not due to great admixture of it with other bodies of water, but is due to the crowding together of the density lines over the " Sill ". As with the salinity, temperature and oxygen figures, the lines showing the outflow of deep Red Sea water are not continuous over the " Sill ". The probable explanation of this phenomenon has already been given.

From these four figures (6, 7, 8 and 9) it can be clearly seen that there are three bodies of water, distinct in both properties and origin, flowing over the " Sill ". At the surface

there is the light, high temperature, high oxygen, and high salinity water flowing from the Red Sea to the Gulf of Aden under the influence of the prevailing NNW. winds of this season. This flow extends to various depths, but shows an average depth of about 40–50 metres. Below this is a low salinity, low temperature and low oxygen body of water, of moderate density flowing from the Gulf of Aden to the Red Sea to compensate for the water lost from here by evaporation and in the wind- and bottom-currents.

At the bottom there is every indication that there is a temporary outflow of deep Red Sea water of very high salinity, high density, comparatively high oxygen concentration

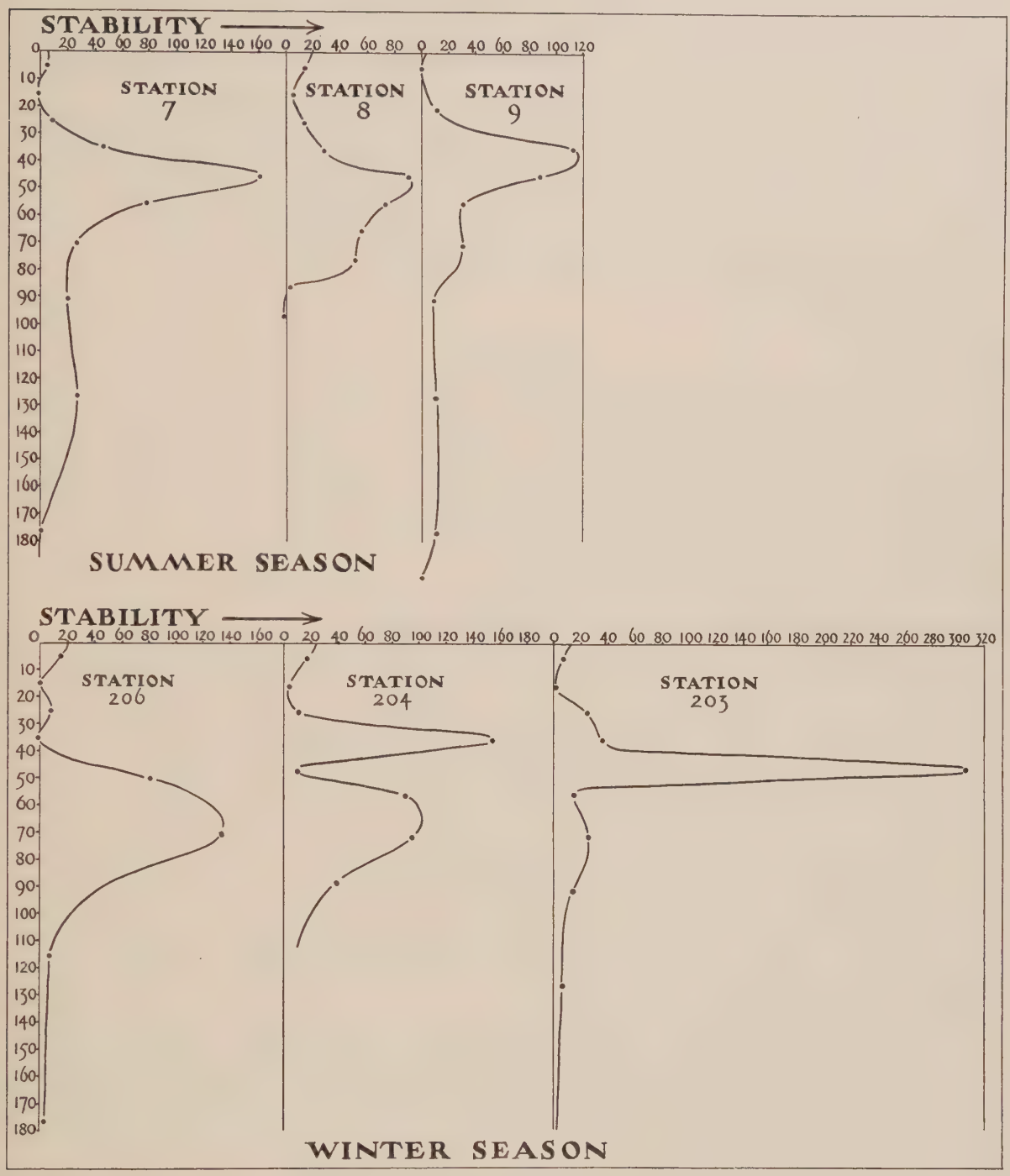


Text-fig. 9.

and moderate temperature. This flow, however, is almost certainly transitory, occurring only during the flood tide in accordance with the observations of Vercelli (1927).

A comparison of the winter and summer seasons elucidates many of the points which previous workers have been forced to neglect through lack of knowledge of the summer conditions and of the circulation of the Red Sea, which I have discussed in a previous paper (Thompson, 1939). In the first place it has been shown that the type of circulation in the two seasons is essentially different. While in the summer there are three distinct water masses moving over the " Sill ", in the winter months we have but two, the middle one having now disappeared and the surface one now moving in the opposite direction, and having a different source. The conclusions of Schott (1929), in which he considered that the inflowing winter current was continuous with the Gulf of Aden water below

100 metres, has been shown to be entirely erroneous. The lower part of the current is really part of the middle summer current shown in the figures for this season, and which is completely blocked in the winter by the increased outflow of deep Red Sea water.



Text-fig. 10.

The outflow of deep Red Sea water is shown to be very much greater in the winter than in the summer months, and while this may be due in part to the state of the tide during these observations, the explanation is probably to be found in the nature of the

Red Sea circulation previously described (Thompson, 1939). It was there shown that during the winter months there would tend to be an upward movement of the deep Red Sea water against the " Sill ", while during the summer the movement would be in the opposite direction. Such a movement would tend to push this water over the " Sill " in the winter months, and hinder its passage in this direction during the other season. In addition the production of this deep highly saline water is confined to the mid-winter months. This also would tend to increase its outflow in the winter season.

Schott, in his conclusions on this area, points out that the winds during the summer season would be such as to retard the inflow of water into the Red Sea just at that period when, evaporation being at a maximum, a compensating inflowing current would be most needed. The solution to this problem is found in the nature of the summer circulation as here described, the necessary compensation for evaporation being provided by the cold inflowing intermediate stream.

SUMMARY.

1. It is shown that the exchange over the " Sill " between the Red Sea and the Gulf of Aden is fundamentally different in the winter and summer seasons. In the winter there are but two masses of water moving over the " Sill, " a surface very warm layer entering the Red Sea from the Gulf of Aden, and a deep outflow of very saline water from the Red Sea. In the summer there are three bodies of water moving over the " Sill " ; a wind-driven surface mass of high temperature water flowing out of the Red Sea into the Gulf of Aden ; a bottom very saline outflow from the Red Sea ; and an intermediate low salinity low temperature inflow from the Gulf of Aden into the Red Sea.

2. Schott has confused the *Winter Surface* inflow with the Summer *intermediate* inflow. It is shown here that these two bodies of water are of entirely different characteristics, contribute but little to each other, and are confined in this region to opposite seasons. Schott's confusion of these two bodies of water prevented him from explaining the compensation for evaporation and other losses in the Red Sea during the summer season. It seems clear from the previous discussions that this compensation is effected by the cold, low salinity intermediate stream which is confined to the summer season.

3. It is shown that the outflow of highly saline deep Red Sea water is much greater during the winter than the summer months. This is due to : (*a*) This water is being produced at this season in the northern Red Sea ; (*b*) the rotational effect due to the inflowing surface water which piles up in the region of latitude 20° N., and projects the deep Red Sea water up over the " Sill ".

4. It is suggested that the outflow of this deep Red Sea water is effected by tidal oscillations in such a way that the flow is at a maximum over the flood, and at a minimum over the ebb tide. While the interruption of the deep outflow at the ebb tide seems to be complete during the summer, it appears that this is never so in the winter months.

ACKNOWLEDGMENT.

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